

Digital Image Correlation : Howto

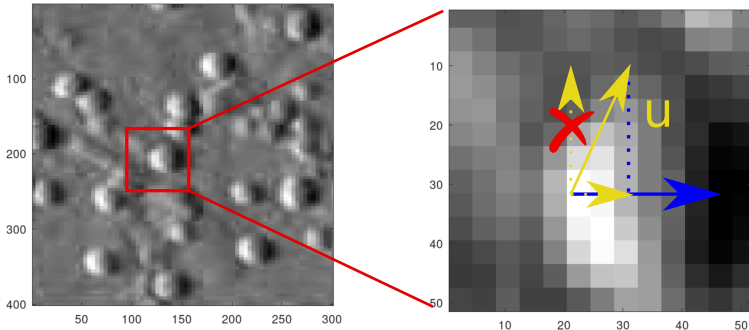
F. Amiot

Université Marie et Louis Pasteur, FEMTO-ST Institute CNRS-UMR 6174



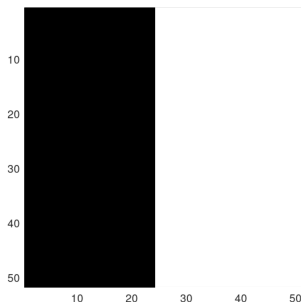
DIC in 1 slide

- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory



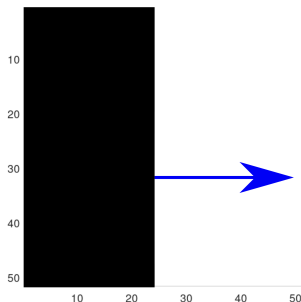
DIC in 1 slide

- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory



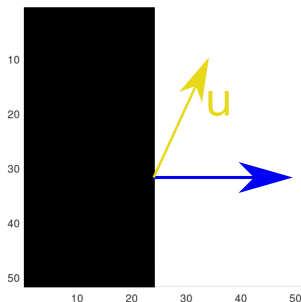
DIC in 1 slide

- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory



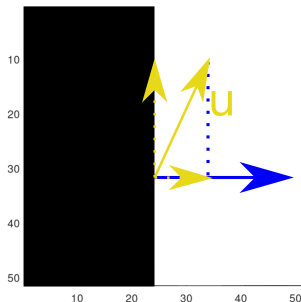
DIC in 1 slide

- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory



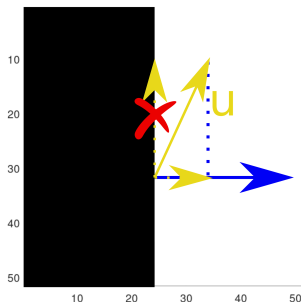
DIC in 1 slide

- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory



DIC in 1 slide

- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory



DIC in 1 slide



- ▶ A method making use of at least 2 gray-scale images of your sample : one 'reference' image and one 'deformed' image to yield a displacement field
- ▶ A pattern providing sufficient contrast must be integral to the part
- ▶ The gradient it provides carries the information about surface displacements
- ▶ In 2D, the problem is however ill-posed, and regularization is mandatory
- ▶ Different assumptions can be made for regularization, leading to different families of algorithms



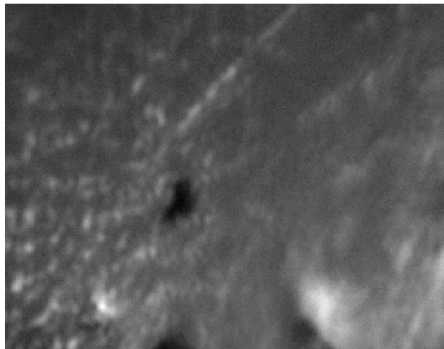
Many opensource options

- ▶ **Dolfin Warp** : Finite element motion tracking (DIC/DVC) python library based on FEniCS + VTK, with a **tutorial**.
- ▶ **Kintsugi** : Global DIC/DVC with mechanical regularization, with python and C++ interfaces (no tutorial).
- ▶ **Pyxel** : Open-source python FE DIC/DVC library for experimental mechanics, with few examples.
- ▶ **Spam** : DVC and other image analysis tools for material analysis using python.
- ▶ **UFreckles** : 2D/2.5D/3D DIC MatLab software using finite element motion tracking with mechanical regularization.
- ▶ **Ncorr** : Open source 2D DIC MATLAB program.
- ▶ **Mecapix** : online DIC (local/global) developed for practical works at the **Mecamat conference**. May require a .fr email address.
- ▶ **Pydic** : Small and versatile python library for local 2D DIC based on optical flow.

The pattern is the key...



- ▶ The pattern should generate gradients in the image...
- ▶ Isotropic orientation,
- ▶ at the scale of your subset/finite-element.
- ▶ The natural texture may be sufficient
- ▶ Trade-off with the required regularization



A pattern at the micro-/nano-scale ?

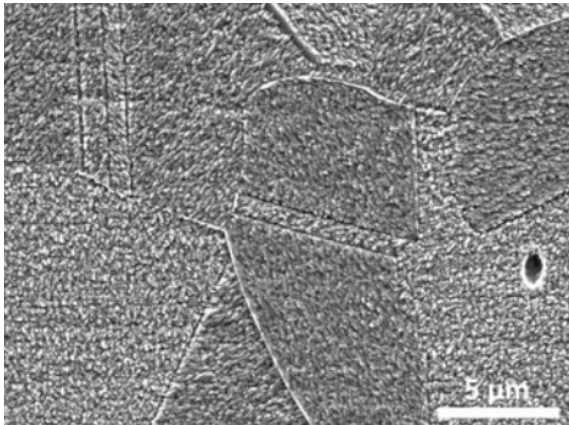


- ▶ Microstructure-based speckle patterns
- ▶ Templated patterns
- ▶ Particle deposition
- ▶ Thin film remodeling
- ▶ (based on a compilation made by D. Texier, ICA)



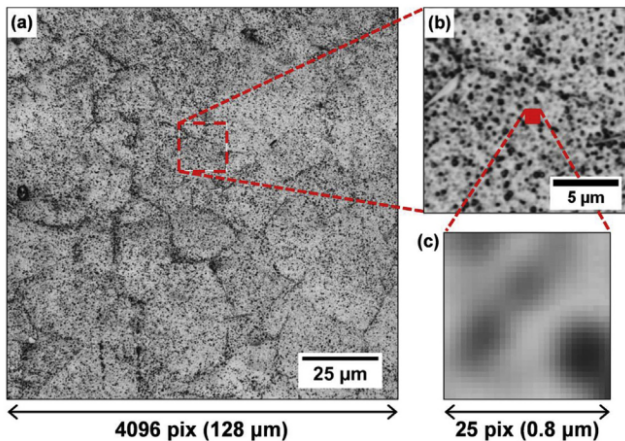
Microstructure-based speckle patterns : chemical etching

Etching (copper, e^-), EBSD possible



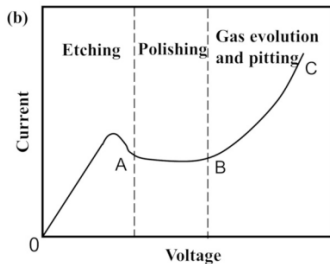
Microstructure-based speckle patterns : chemical etching

Etching (Inconel718, optical)



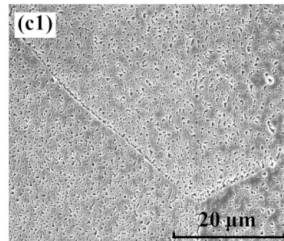
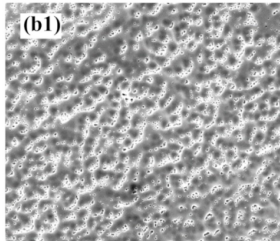
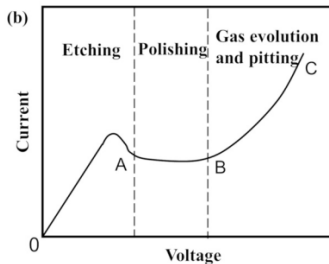
Microstructure-based speckle patterns : chemical etching

(over-) Electro-polishing (Aluminum alloy, e^-)



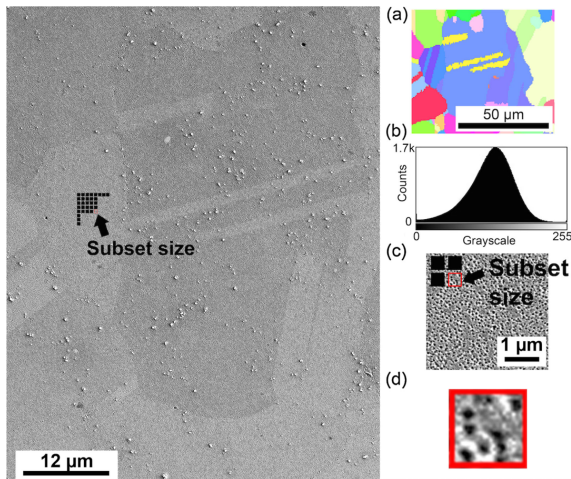
Microstructure-based speckle patterns : chemical etching

(over-) Electro-polishing (Aluminum alloy, e^-)



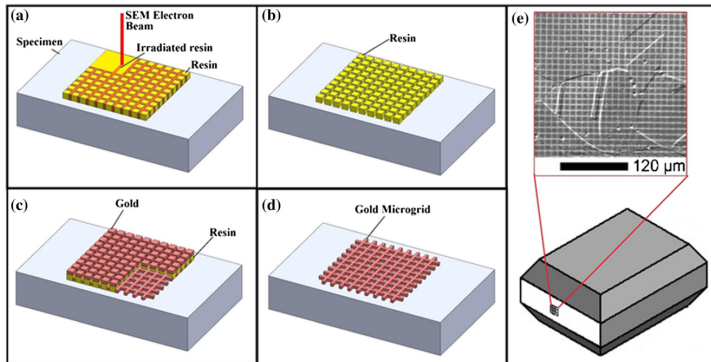
Microstructure-based speckle patterns : pre-oxidation

Oxidation+Etching (Rene88DT, e^-)



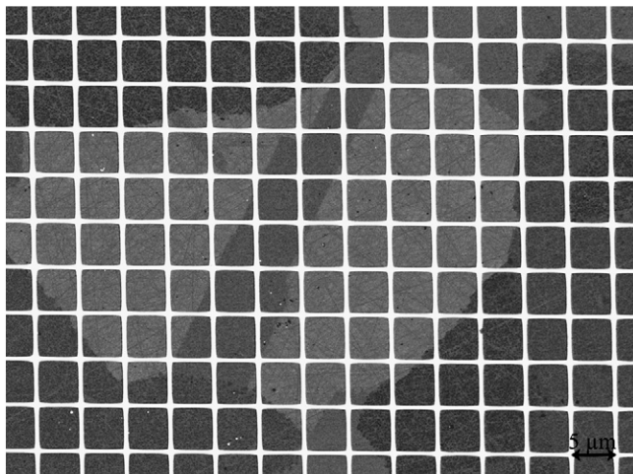
Templated patterns : photo- / electro-lithography

Electronic lithography (Fe-Ni alloy, e^-) : gold grid



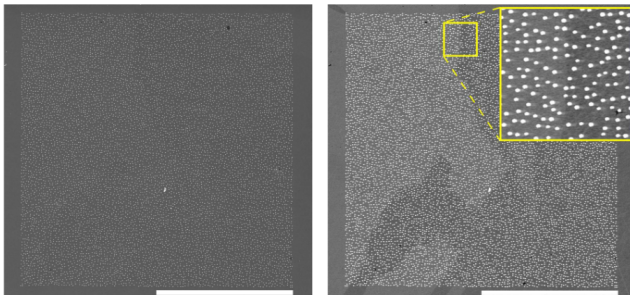
Templated patterns : photo- / electro-lithography

Electronic lithography (NR6 superalloy, e^-) : high temperature : HfO_2



Templated patterns : photo- / electro-lithography

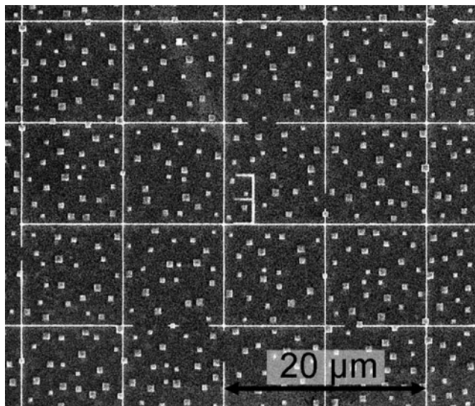
Electronic lithography (e^- , SE / BSE)



Advantage of the templated patterns : distortions may be identified

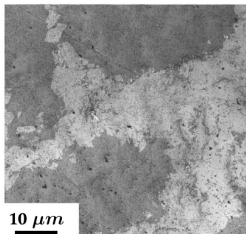
Templated patterns : photo- / electro-lithography

Electronic lithography (Rene104, e^-) HfO_2 pattern

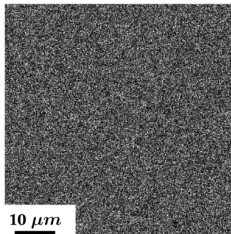


Templated patterns : FIB milling

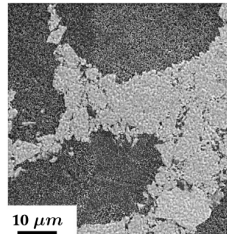
FIB milling (Two phases Al alloy, e^-)



(b) Zone Z1 before patterns



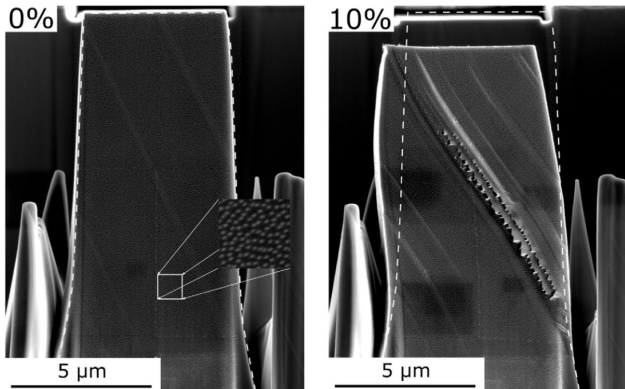
(c) Speckled patterns



(d) Zone Z1 Speckled patterns

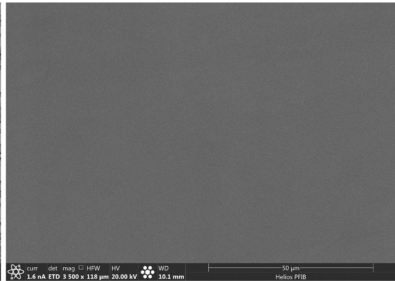
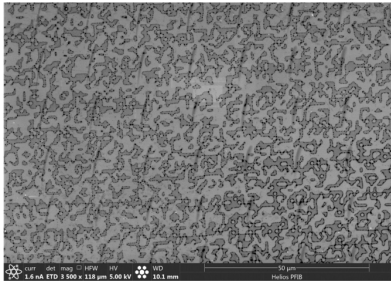
Templated patterns : FIB deposition

FIB deposition (TiAl alloy, e^-) : Pt pattern



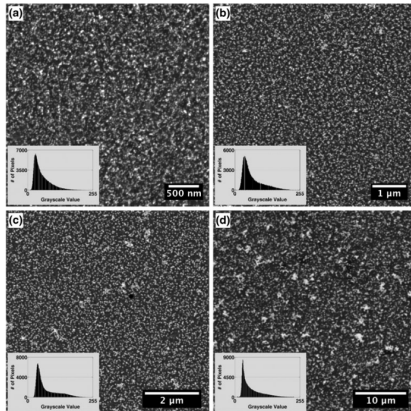
Templated patterns : stamping

Stamping (AlCu alloy, e^- : SE / BSE)



Particle deposition : wet colloidal method

Wet colloidal method (Al alloy, silicon carbide, Ni superalloy, e^-) : nano-particles

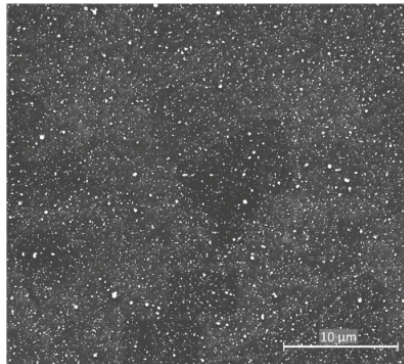
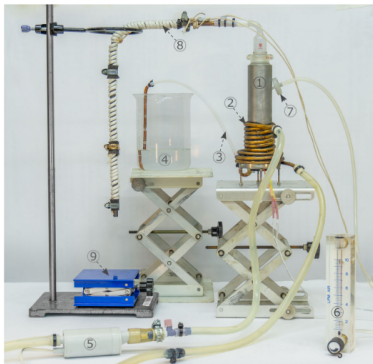


tutorial

Adaptable to sensitive materials using non-aqueous solvents

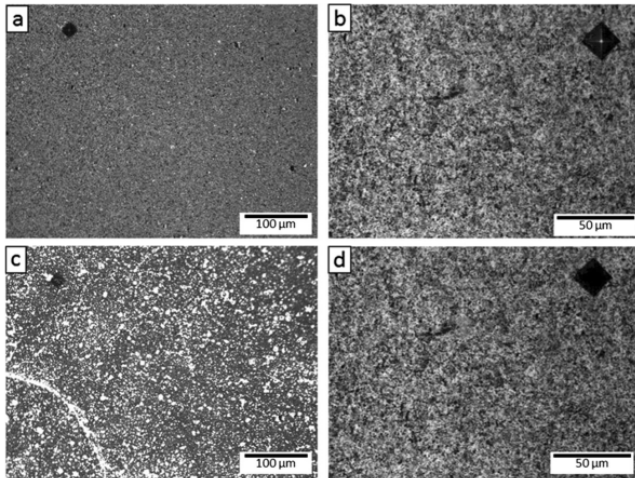
Particle deposition : nebulization

Nebulization (Steel, e^-) : silica nanoparticles



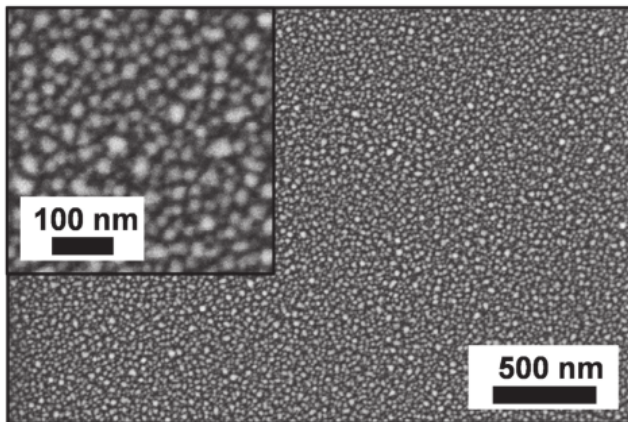
Particle deposition : dry blasting

Dry-blasting (Ni superalloy, optical) : Si, alumina



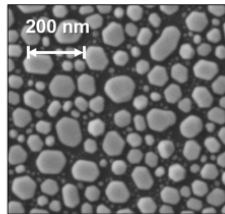
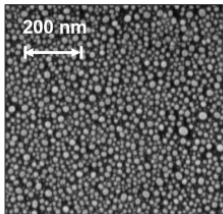
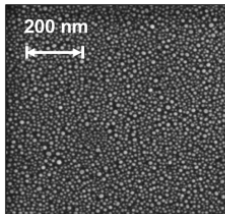
Particle deposition : dry deposition

Magnetron sputtering (Si wafer, e^-) : InSn deposition



Particle deposition : dry deposition

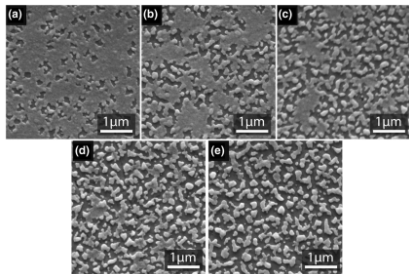
Evaporation (Si wafer, e^-) : In e-beam evaporation



Thin film remodeling

Thin film remodeling (Epoxy-glass composite, e^-) : silver + NaCl

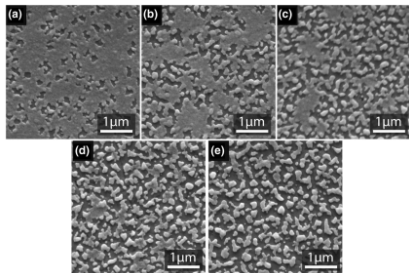
With time :



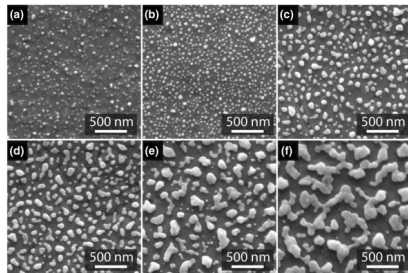
Thin film remodeling

Thin film remodeling (Epoxy-glass composite, e^-) : silver + NaCl

With time :

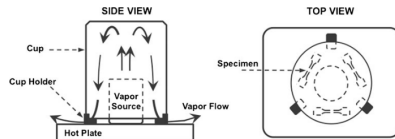
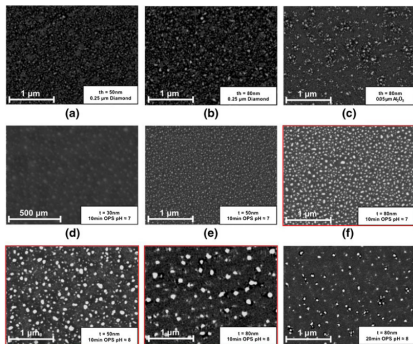


With thickness :



Thin film remodeling

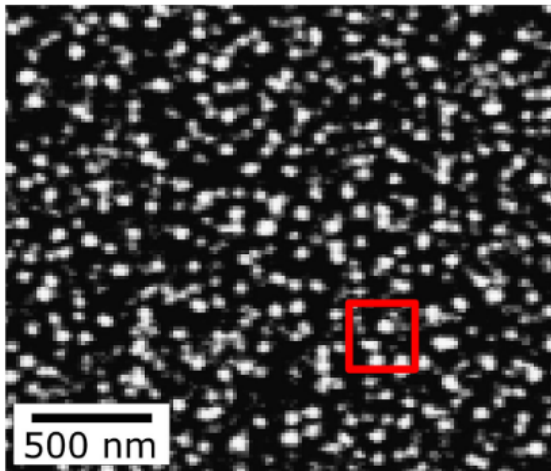
Thin film remodeling (Stainless steel, e^-) : gold and water vapor



Tutorial

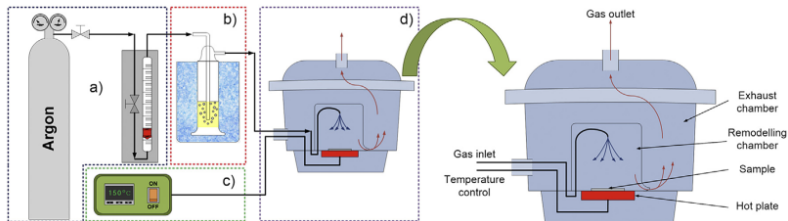
Thin film remodeling

Thin film remodeling (CuCrZr, e^-) : non-aqueous solvent + NaBr



Thin film remodeling

Thin film remodeling (Magnesium alloy, e^-)



Your choice...

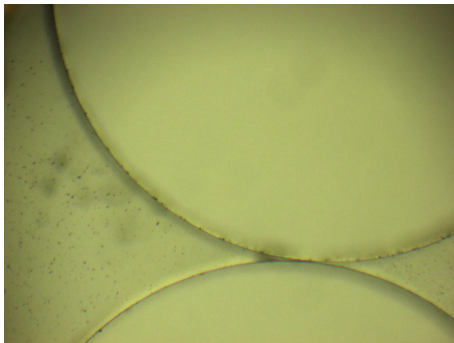


- ▶ Does the patterning technique significantly modify my material? (corrosion, pitting, etc)
- ▶ Temperature?
- ▶ EBSD at the same time?
- ▶ Use for distortion corrections?
- ▶ Field of view? Cost?



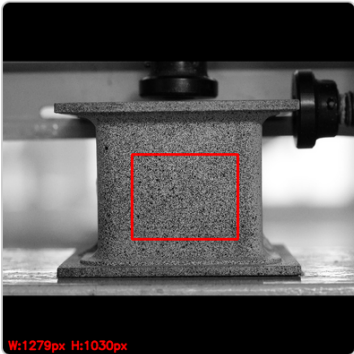
What is a good image?

- ▶ Good contrast (no saturation, widespread GL distribution)
- ▶ Avoid image compression
- ▶ Spatial resolution should be enough to catch the pattern :
at least 3 pix $\simeq$ correlation length
- ▶ The intensity changes reflect the sole displacement field. Typical error sources (optical) :
 - ▶ Non-uniform illumination? Vignetting?
 - ▶ Out-of-plane displacements ?
 - ▶ Distortions ?



Selecting the parameters

simple_shear_0



W:1279px H:1030px

simple_shear_1



Algorithms:

☐ PyDic (*)

☐ pyxel (*)

☒ FE-Global-ECN (*)

(*) [see Credits](#)

Parameters:

Element size (px):

Coarse Gr. Scale:

☐ Regularisation

Mask settings

Speckle analysis

Solve

Selecting the parameters : element size

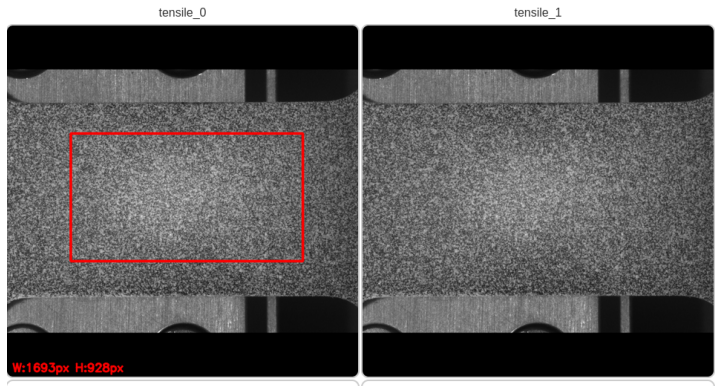


- ▶ A minimal size : at least few 'spots' inside a window
- ▶ A trade-off :
 - ▶ Small elements allow to describe very non-uniform strain fields...
 - ▶ ... but are more sensitive to noise.
 - ▶ (Too)Large elements are not able to describe non-uniform strain fields...
 - ▶ ... but are very robust to noise.
- ▶ Do you need a very spatially resolved measurement?



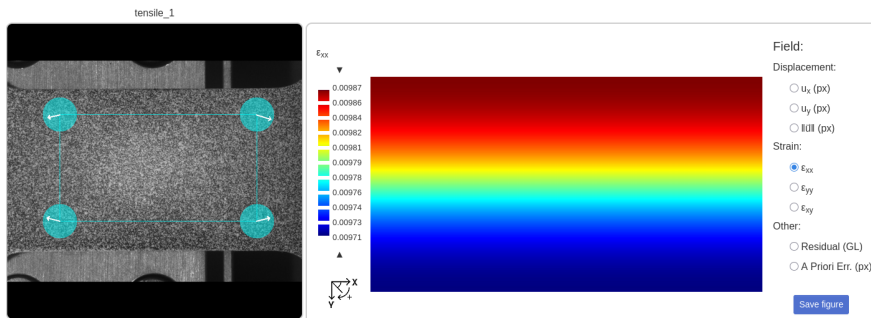
Selecting the parameters : element size

- ▶ Do you need a very spatially resolved measurement?
- ▶ Example : tensile test to retrieve isotropic elastic parameters



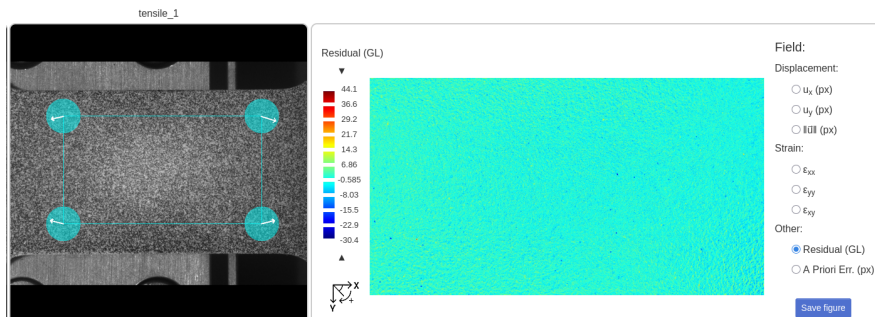
Selecting the parameters : element size

- ▶ Do you need a very spatially resolved measurement?
- ▶ Example : tensile test to retrieve isotropic elastic parameters



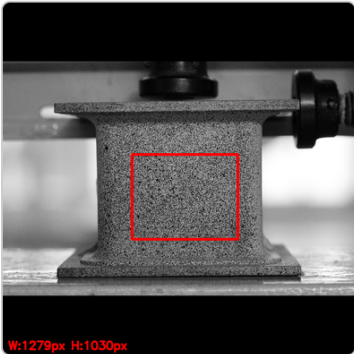
Selecting the parameters : element size

- ▶ Do you need a very spatially resolved measurement?
- ▶ Example : tensile test to retrieve isotropic elastic parameters



Selecting the parameters

simple_shear_0



W:1279px H:1030px

simple_shear_1



Algorithms:

☐ PyDic (*)

☐ pyxel (*)

☒ FE-Global-ECN (*)

(*) [see Credits](#)

Parameters:

Element size (px):

Coarse Gr. Scale:

☐ Regularisation

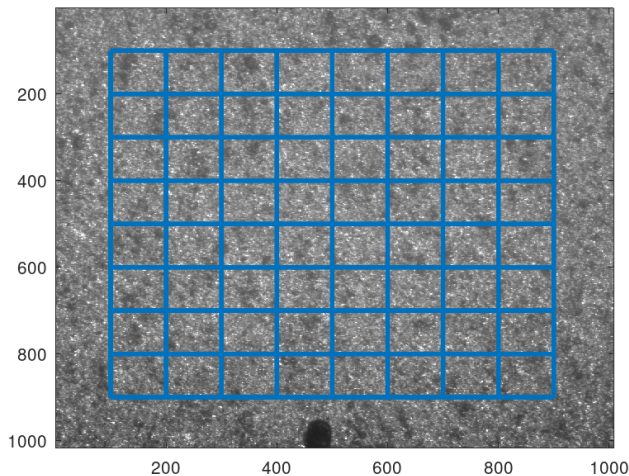
Mask settings

Speckle analysis

Solve

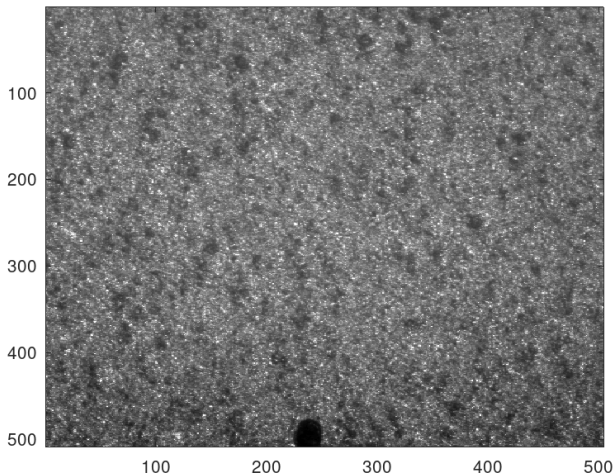
Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.



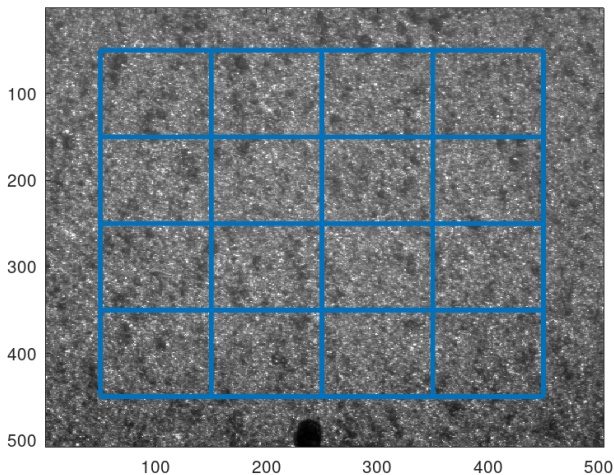
Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.



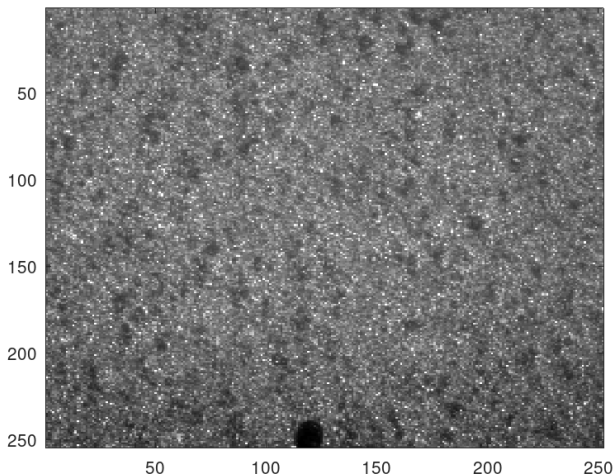
Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.



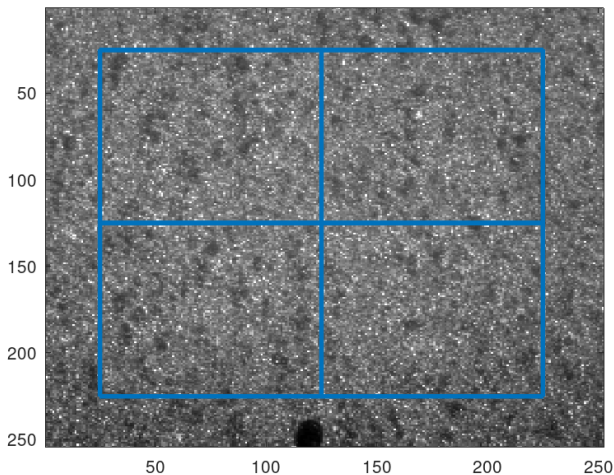
Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.



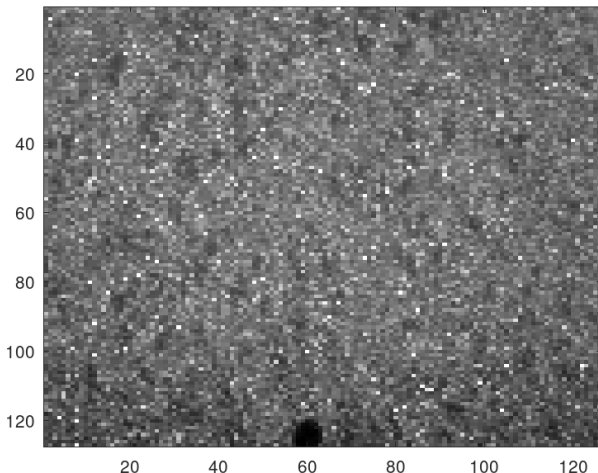
Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.



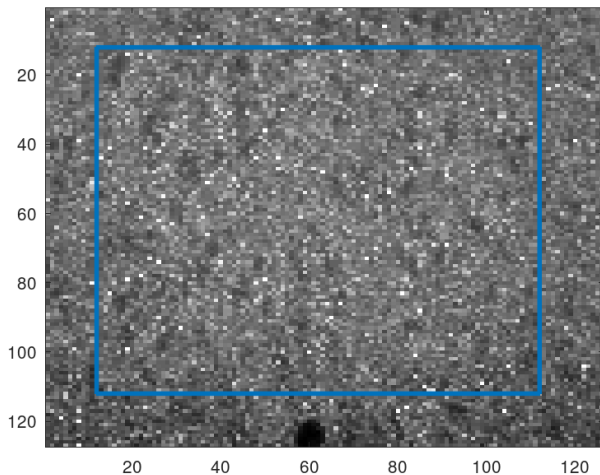
Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.



Selecting the parameters : coarse-graining

Remember : DIC is a non-linear minimization problem, which requires initialization.

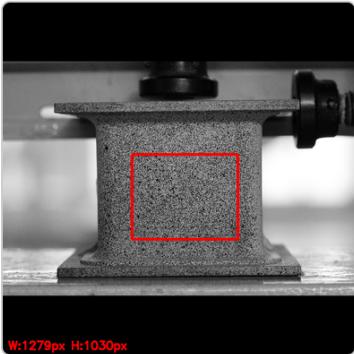


Selecting the parameters : coarse-graining

- ▶ Multi-grid solver :
 - ▶ Initialize the coarsest grid using rigid-body motion (FFT)
 - ▶ Use the FE interpolation to initialize the computation at next level
 - ▶ Perform the computation
 - ▶ Use the result and FE interpolation to initialize the computation at next level
 - ▶ iterate until you achieve the desired discretization
- ▶ The coarse-graining number is the number of scales
- ▶ Should be high enough, especially if large displacement increments are expected
- ▶ Usually avoids local minima

Selecting the parameters

simple_shear_0



W:1279px H:1030px

simple_shear_1



Algorithms:

☐ PyDic (*)

☐ pyxel (*)

☒ FE-Global-ECN (*)

(*) [see Credits](#)

Parameters:

Element size (px):

Coarse Gr. Scale:

☐ Regularisation

Mask settings

Speckle analysis

Solve

Good practices

At least :

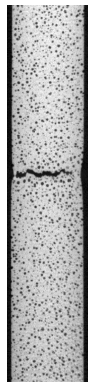
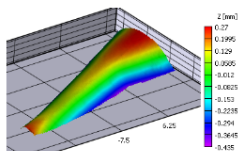
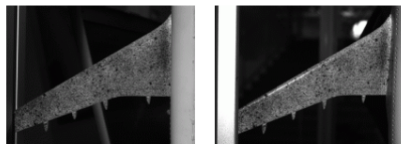
- ▶ Take 10-100 images of your unloaded sample, and perform DIC with your actual parameters : noise floor. Drifts?
- ▶ Carefully select the algorithm parameters
- ▶ Check for convergence
- ▶ Always carefully check the residuals map!
 - ▶ Few % of your full GL scale
 - ▶ No localization

To go further :

- ▶ Numerically impose rigid body motions/uniform strain to your reference image, and perform DIC with your actual parameters : systematic errors and uncertainties as a function of the element size
- ▶ For templated patterns : use them to identify **distorsions**

Concluding remarks

- ▶ DIC may give access to **surface** displacements. Assumptions are required for extending the field in the bulk
- ▶ Integrated approaches (with an underlying mechanical model) are very useful for difficult measurements
- ▶ All these approaches extend to 2.5D (stereo-correlation) or 3D (DVC)

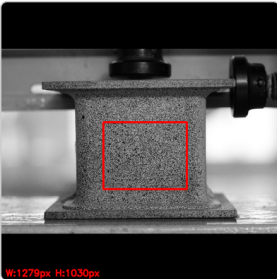


Concluding remarks

► Try?

- **Mecapix** : <https://mecapix.ec-nantes.fr/> with a (fake) .fr email
- your images?

simple_shear_0



W:1279px H:1030px

simple_shear_1



Algorithms:

☐ PyDic (*)
☐ pyxel (*)
☒ FE-Global-ECN (*)

(*) see Credits

Parameters:

Element size (px):

Coarse Gr. Scale:

☐ Regularisation

Mask settings

Speckle analysis Solve

Resources



- ▶ Mecamat working group (with workshops dedicated to measurements at microscale)
- ▶ PhotoMeca association
- ▶ Mecamat Aussois colloquium on full-field measurements
- ▶ IdICs good practices guide
- ▶ Assessment of Digital Image Correlation Measurement Errors: Methodology and Results
- ▶ Assessment of Digital Image Correlation Measurement Accuracy in the Ultimate Error Regime: Main Results of a Collaborative Benchmark

